

The Glashow resonance as a discriminator of UHE cosmic neutrinos originating from $p\gamma$ and pp collisions

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Abstract

We re-examine the interesting possibility of utilizing the Glashow resonance (GR) channel $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$ to discriminate between the UHE cosmic neutrinos originating from $p\gamma$ and pp collisions in an optically thin source of cosmic rays. We propose a general parametrization of the initial neutrino flavor composition by allowing the ratios $\Phi_{\pi^-}^{p\gamma}/\Phi_{\pi^+}^{p\gamma}$ and $\Phi_{\pi^-}^{pp}/\Phi_{\pi^+}^{pp}$ to slightly deviate from their conventional values. A relationship between the typical source parameter $\kappa \equiv (\Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^-}^{p\gamma})/(\Phi_{\pi^+}^{pp} + \Phi_{\pi^-}^{pp} + \Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^-}^{p\gamma})$ and the working observable of the GR $R_0 \equiv \Phi_{\bar{\nu}_e}^T/(\Phi_{\nu_\mu}^T + \Phi_{\bar{\nu}_\mu}^T)$ at a neutrino telescope is derived, and the numerical dependence of R_0 on κ is illustrated by taking account of the latest experimental data on three neutrino mixing angles. It is shown that a measurement of R_0 is in principle possible to identify the pure $p\gamma$ interaction ($\kappa = 1$), the pure pp interaction ($\kappa = 0$) or a mixture of both of them ($0 < \kappa < 1$) at a given source of UHE cosmic neutrinos. The event rate of the GR signal against the background is also estimated.

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1 Introduction

The full construction of the IceCube detector [1], a km^3 -scale neutrino telescope at the South Pole, has recently been completed. It offers a great opportunity to discover ultrahigh-energy (UHE) cosmic neutrinos, whose existence may hopefully allow us to pin down the origin of UHE cosmic rays. The reason is simply that the UHE cosmic protons originating in a cosmic accelerator, such as a gamma ray burst or active galactic nuclei [2], unavoidably interact with ambient photons or protons. Such energetic pp or $p\gamma$ interactions produce a large amount of charged pions, from which UHE cosmic neutrinos can copiously be produced. Since UHE cosmic neutrinos are not deflected by the interstellar magnetic field, they can be used to locate the cosmic accelerators if they are observed in a terrestrial neutrino telescope.

The $p\gamma$ and pp collisions at an optically thin source of UHE cosmic rays are usually referred to as the conventional production mechanism of UHE cosmic neutrinos. Charged pions are mainly produced via $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$ in the $p\gamma$ interaction or $p + p \rightarrow \pi^\pm + X$ with X being other particles in the pp interaction [3]. So neutrinos arise from the decay chain $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$ and its charge-conjugate process. In an astrophysical source of either $p\gamma$ or pp collisions one has the same $\nu_\alpha + \bar{\nu}_\alpha$ flavor distribution $\Phi_e^S : \Phi_\mu^S : \Phi_\tau^S = 1 : 2 : 0$, where $\Phi_\alpha^S \equiv \Phi_{\nu_\alpha}^S + \Phi_{\bar{\nu}_\alpha}^S$ with $\Phi_{\nu_\alpha}^S$ and $\Phi_{\bar{\nu}_\alpha}^S$ being the fluxes of ν_α and $\bar{\nu}_\alpha$ (for $\alpha = e, \mu, \tau$) at the source. This initial flavor distribution is expected to change to $\Phi_e^T : \Phi_\mu^T : \Phi_\tau^T = 1 : 1 : 1$ at a neutrino telescope such as the IceCube, because UHE cosmic neutrinos may oscillate many times on the way to the Earth and finally reach a flavor democracy [4] if the 3×3 neutrino mixing matrix V satisfies the $|V_{\mu i}| = |V_{\tau i}|$ condition (for $i = 1, 2, 3$) [5]. Provided such a flavor democracy is really measured at the IceCube detector or at a more advanced neutrino telescope in the future, one will be essentially convinced that the measured UHE cosmic neutrinos come from the $p\gamma$ or pp collisions (or a mixture of both of them) in a distant cosmic accelerator. Then an immediate and meaningful question is whether the neutrino telescope can discriminate between the $p\gamma$ and pp interactions at the source.

The answer to the above question is in principle affirmative, if the ν_e and $\bar{\nu}_e$ fluxes can separately be determined at a neutrino telescope. Unfortunately, the present IceCube detector is unable to distinguish between the Cherenkov light patterns arising from the interactions of ν_e and $\bar{\nu}_e$ with ice. A possible way out is to detect the UHE cosmic $\bar{\nu}_e$ flux by means of the Glashow resonance (GR) channel $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$ [6, 7], whose cross section can be about two orders of magnitude larger than the cross sections of $\bar{\nu}_e N$ interactions around the resonant energy $E_{\bar{\nu}_e} \simeq 6.3 \text{ PeV}$ [8]. As pointed out by Anchordoqui *et al* [9], the GR may serve for a useful discriminator of UHE cosmic neutrinos originating from $p\gamma$ and pp collisions in an optically thin source of cosmic rays. The main purpose of the present paper is to re-examine this interesting possibility by paying particular attention to the flavor content of UHE cosmic neutrinos and its variation from a source to a telescope.

Our work is different from the previous attempts in this connection (e.g., Ref. [4] and Refs. [9]–[13]) in several aspects. First, we propose a general parametrization of the initial flavor distribution of UHE cosmic neutrinos originating from $p\gamma$ and pp collisions by allowing

$\Phi_{\pi^-}^{p\gamma}/\Phi_{\pi^+}^{p\gamma} \neq 0$ and $\Phi_{\pi^-}^{pp}/\Phi_{\pi^+}^{pp} \neq 1$. This treatment makes sense as the assumptions $\Phi_{\pi^-}^{p\gamma} = 0$ (in the $p\gamma$ interaction) and $\Phi_{\pi^-}^{pp} = \Phi_{\pi^+}^{pp}$ (in the pp interaction) may not exactly hold in a realistic cosmic accelerator. Second, we establish an analytical relationship between three typical source parameters ($\delta_{p\gamma} \equiv \Phi_{\pi^-}^{p\gamma}/\Phi_{\pi^+}^{p\gamma}$, $\delta_{pp} \equiv \Phi_{\pi^-}^{pp}/\Phi_{\pi^+}^{pp} - 1$ and $\kappa \equiv [\Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^-}^{p\gamma}]/[\Phi_{\pi^+}^{pp} + \Phi_{\pi^-}^{pp} + \Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^-}^{p\gamma}]$) and the working observable of the GR ($R_0 \equiv \Phi_{\bar{\nu}_e}^T/[\Phi_{\nu_\mu}^T + \Phi_{\bar{\nu}_\mu}^T]$) at a neutrino telescope[‡]. Third, we examine the numerical dependence of R_0 on κ by taking account of the latest experimental data on three neutrino mixing angles. Our result shows that a measurement of R_0 is in principle possible to identify the pure $p\gamma$ interaction ($\kappa = 1$), the pure pp interaction ($\kappa = 0$) or a mixture of both of them ($0 < \kappa < 1$) at a given astrophysical source, in particular after all the neutrino mixing parameters of V are well determined from a variety of terrestrial neutrino oscillation experiments. In addition, the event rate of the GR signal against the relevant background is also estimated in this paper.

2 Modified Flavor Distribution on the GR

We have denoted the π^\pm fluxes from the $p\gamma$ interaction as $\Phi_{\pi^\pm}^{p\gamma}$, and those from the pp interaction as $\Phi_{\pi^\pm}^{pp}$. In the conventional picture of $p\gamma$ collisions one mainly considers the Δ -resonance channel $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$, and thus $\Phi_{\pi^-}^{p\gamma} = 0$ is taken as a good approximation for a given astrophysical source. As for the pp interaction in a cosmic accelerator, the produced π^+ , π^- and π^0 mesons are expected to be in almost equal amount due to the isospin symmetry. Hence $\Phi_{\pi^-}^{pp} = \Phi_{\pi^+}^{pp}$ is also a good approximation. In general, however, a small amount of π^- mesons should be produced from the $p\gamma$ interaction (e.g., from the multi-pion production channel $p + \gamma \rightarrow n + \pi^+ + \mathbf{n}(\pi^+\pi^-)$ with \mathbf{n} being a positive integer [14][§]), and a slight difference between $\Phi_{\pi^-}^{pp}$ and $\Phi_{\pi^+}^{pp}$ must be present for the pp interaction. So we consider a general source in which both $p\gamma$ and pp collisions are important. To be explicit, we define three typical source parameters to describe the content of π^+ and π^- mesons produced from $p\gamma$ and pp collisions: $\delta_{p\gamma} \equiv \Phi_{\pi^-}^{p\gamma}/\Phi_{\pi^+}^{p\gamma}$, $\delta_{pp} \equiv \Phi_{\pi^-}^{pp}/\Phi_{\pi^+}^{pp} - 1$ and

$$\kappa \equiv \frac{\Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^-}^{p\gamma}}{\Phi_{\pi^+}^{pp} + \Phi_{\pi^-}^{pp} + \Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^-}^{p\gamma}}. \quad (1)$$

In this simple parametrization the $\kappa = 1$ and $\kappa = 0$ cases correspond to the pure $p\gamma$ and pure pp interactions, respectively. If the value of κ is found to lie in the $0 < \kappa < 1$ range at a neutrino telescope, it will imply that both $p\gamma$ and pp collisions exist at the relevant astrophysical source.

Now we look at the flavor composition of UHE cosmic neutrinos originating from $p\gamma$ and pp collisions in an optically thin source of cosmic rays. Taking account of κ , $\delta_{p\gamma}$ and δ_{pp} defined

[‡]Note that X_γ and T have been used in Ref. [11] to describe the fraction of UHE cosmic neutrinos produced from the $p\gamma$ interaction and the working observable at the neutrino telescope, respectively.

[§]Note that the back reaction $n + \gamma \rightarrow p + \pi^-$ could also produce π^- mesons if the optical thickness of the source is non-negligible, and the $\bar{\nu}_e$ flux originating from the beta decays of neutrons might even dominate in some astrophysical sources for very specific energy ranges [12]. For simplicity, here we follow Ref. [9] and focus on the cases in which the afore-mentioned effects can be neglected.

above, we obtain the ratio of neutrino and antineutrino fluxes as follows:

$$\begin{aligned}
& \left\{ \Phi_{\nu_e}^S : \Phi_{\bar{\nu}_e}^S : \Phi_{\nu_\mu}^S : \Phi_{\bar{\nu}_\mu}^S : \Phi_{\nu_\tau}^S : \Phi_{\bar{\nu}_\tau}^S \right\} \\
&= (\Phi_{\pi^+}^{p\gamma} + \Phi_{\pi^+}^{pp}) \left\{ \frac{1}{3} : 0 : \frac{1}{3} : \frac{1}{3} : 0 : 0 \right\} + (\Phi_{\pi^-}^{p\gamma} + \Phi_{\pi^-}^{pp}) \left\{ 0 : \frac{1}{3} : \frac{1}{3} : \frac{1}{3} : 0 : 0 \right\} \\
&= \left\{ \frac{1}{3} \left[\frac{1}{2 + \delta_{pp}} + \frac{1 + \delta_{pp} - \delta_{p\gamma}}{(2 + \delta_{pp})(1 + \delta_{p\gamma})} \kappa \right] : \frac{1}{3} \left[\frac{1 + \delta_{pp}}{2 + \delta_{pp}} - \frac{1 + \delta_{pp} - \delta_{p\gamma}}{(2 + \delta_{pp})(1 + \delta_{p\gamma})} \kappa \right] : \frac{1}{3} : \frac{1}{3} : 0 : 0 \right\}. \quad (2)
\end{aligned}$$

Given the definition $\Phi_\alpha^S \equiv \Phi_{\nu_\alpha}^S + \Phi_{\bar{\nu}_\alpha}^S$ (for $\alpha = e, \mu, \tau$), it is straightforward to arrive at the conventional $\nu_\alpha + \bar{\nu}_\alpha$ flavor distribution $\Phi_e^S : \Phi_\mu^S : \Phi_\tau^S = 1 : 2 : 0$. This simple result is completely independent of three source parameters. That is why one has to separately measure the ν_e and $\bar{\nu}_e$ fluxes at a neutrino telescope so as to probe $\Phi_{\nu_e}^S$ and $\Phi_{\bar{\nu}_e}^S$ at the astrophysical source.

Thanks to the effect of neutrino oscillations, the ν_β and $\bar{\nu}_\beta$ fluxes observed at the telescope are simply given by

$$\begin{aligned}
\Phi_{\nu_\beta}^T &= \sum_\alpha (\Phi_{\nu_\alpha}^S P_{\alpha\beta}) , \\
\Phi_{\bar{\nu}_\beta}^T &= \sum_\alpha (\Phi_{\bar{\nu}_\alpha}^S \bar{P}_{\alpha\beta}) , \quad (3)
\end{aligned}$$

where $P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta)$ and $\bar{P}_{\alpha\beta} \equiv P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ stand respectively for the oscillation probabilities of UHE cosmic neutrinos and antineutrinos. Since the galactic distances far exceed the observed solar and atmospheric neutrino oscillation lengths, $P_{\alpha\beta}$ and $\bar{P}_{\alpha\beta}$ are actually averaged over many oscillations and thus become energy-independent:

$$P_{\alpha\beta} = \bar{P}_{\alpha\beta} = \sum_i (|V_{\alpha i}|^2 |V_{\beta i}|^2) , \quad (4)$$

where $V_{\alpha i}$ and $V_{\beta i}$ (for $\alpha, \beta = e, \mu, \tau$ and $i = 1, 2, 3$) denote the elements of the 3×3 neutrino mixing matrix V . For our purpose, we are mainly interested in the determination of $\Phi_{\bar{\nu}_e}^T$ via the GR channel $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$. So we establish a link between three source parameters and a working observable at the neutrino telescope:

$$\begin{aligned}
R_0 &\equiv \frac{\Phi_{\bar{\nu}_e}^T}{\Phi_{\nu_\mu}^T + \Phi_{\bar{\nu}_\mu}^T} \\
&= \left[\frac{1 + \delta_{pp}}{2 + \delta_{pp}} - \frac{1 + \delta_{pp} - \delta_{p\gamma}}{(2 + \delta_{pp})(1 + \delta_{p\gamma})} \kappa \right] \frac{P_{ee}}{P_{e\mu} + 2P_{\mu\mu}} + \frac{P_{e\mu}}{P_{e\mu} + 2P_{\mu\mu}} , \quad (5)
\end{aligned}$$

where P_{ee} , $P_{e\mu}$ and $P_{\mu\mu}$ can directly be read off from Eq. (4). After the matrix elements of V are determined to a sufficiently good degree of accuracy in solar, atmospheric, reactor and accelerator neutrino oscillation experiments, a measurement of R_0 at a neutrino telescope will allow one to constrain the source parameters via Eq. (5). There are two special cases, corresponding to the pure $p\gamma$ interaction ($\kappa = 1$) and the pure pp interaction ($\kappa = 0$) at the astrophysical source of cosmic rays:

$$\begin{aligned}
R_0(\kappa = 1) &= \frac{\delta_{p\gamma}}{1 + \delta_{p\gamma}} \cdot \frac{P_{ee}}{P_{e\mu} + 2P_{\mu\mu}} + \frac{P_{e\mu}}{P_{e\mu} + 2P_{\mu\mu}} , \\
R_0(\kappa = 0) &= \frac{1 + \delta_{pp}}{2 + \delta_{pp}} \cdot \frac{P_{ee}}{P_{e\mu} + 2P_{\mu\mu}} + \frac{P_{e\mu}}{P_{e\mu} + 2P_{\mu\mu}} . \quad (6)
\end{aligned}$$

If both $\delta_{p\gamma}$ and δ_{pp} are switched off, then Eq. (5) can be simplified to

$$R_0(\delta_{p\gamma} = \delta_{pp} = 0) = \frac{1 - \kappa}{2} \cdot \frac{P_{ee}}{P_{e\mu} + 2P_{\mu\mu}} + \frac{P_{e\mu}}{P_{e\mu} + 2P_{\mu\mu}}. \quad (7)$$

This result is particularly interesting in the sense that it offers an opportunity to determine κ in a cosmic accelerator from the measurement of R_0 at a neutrino telescope.

In the standard parametrization of V [15], P_{ee} , $P_{e\mu}$ and $P_{\mu\mu}$ can be expressed in terms of three neutrino mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and the Dirac-type CP-violating phase δ as follows:

$$\begin{aligned} P_{ee} &\simeq 1 - \frac{1}{2} \sin^2 2\theta_{12} - \left(2 - \sin^2 2\theta_{12}\right) \sin^2 \theta_{13}, \\ P_{e\mu} &\simeq \frac{1}{2} \sin^2 2\theta_{12} \cos^2 \theta_{23} + \frac{1}{4} \sin 4\theta_{12} \sin 2\theta_{23} \sin \theta_{13} \cos \delta + \left(2 \sin^2 \theta_{23} - \frac{1}{2} \sin^2 2\theta_{12}\right) \sin^2 \theta_{13}, \\ P_{\mu\mu} &\simeq 1 - \frac{1}{2} \sin^2 2\theta_{23} - \frac{1}{2} \sin^2 2\theta_{12} \cos^4 \theta_{23} - \frac{1}{2} \sin 4\theta_{12} \sin 2\theta_{23} \cos^2 \theta_{23} \sin \theta_{13} \cos \delta \\ &\quad + \frac{1}{4} \left[\sin^2 2\theta_{12} \sin^2 2\theta_{23} (2 + \cos 2\delta) - 8 \sin^4 \theta_{23} \right] \sin^2 \theta_{13}, \end{aligned} \quad (8)$$

in which the terms proportional to $\sin^3 \theta_{13} \sim 0.3\%$ and those much smaller ones have been omitted. A global analysis of the latest neutrino oscillation data [16] yield $\sin^2 \theta_{12} = 0.306^{+0.018}_{-0.015}$, $\sin^2 \theta_{13} = 0.021^{+0.007}_{-0.008}$ and $\sin^2 \theta_{23} = 0.42^{+0.08}_{-0.03}$ at the 1σ level [¶], while the Dirac-type CP-violating phase δ remains entirely unrestricted. Because the contributions of δ to P_{ee} , $P_{e\mu}$ and $P_{\mu\mu}$ are always suppressed by small $\sin \theta_{13}$, the δ -induced uncertainties in the calculation of R_0 should not be significant.

Note that a real observable of the GR channel $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$ at a neutrino telescope can be the ratio of the $\bar{\nu}_e$ events to the ν_μ and $\bar{\nu}_\mu$ events of charged-current interactions in the vicinity of the resonance $E_{\bar{\nu}_e} \simeq M_W^2/(2m_e) \simeq 6.3$ PeV [10, 19]:

$$R \equiv \frac{N_{\bar{\nu}_e}}{N_{\nu_\mu}^{\text{CC}} + N_{\bar{\nu}_\mu}^{\text{CC}}} = aR_0, \quad (9)$$

where $a \simeq 30.5$ can be obtained in an optimal case by assuming the $E_{\nu_\alpha}^{-2}$ neutrino spectrum [10] and considering the muon events with contained vertices [18] in a water- or ice-based detector. A more accurate calculation of a is certainly crucial for the IceCube detector to detect the rate of the GR reaction [9]. Note also that the $\bar{\nu}_e$ flux of $E_{\bar{\nu}_e} \simeq 6.3$ PeV might largely get absorbed in passing through the Earth [10]. Hence it is only feasible for a neutrino telescope to detect the downward-going or horizontal $\bar{\nu}_e$ flux whose energy lies in the vicinity of the GR, in which case the atmospheric neutrino flux of the same energy is negligibly small and should not be of concern as an important background [10].

We proceed to illustrate the dependence of R_0 on κ , $\delta_{p\gamma}$ and δ_{pp} with the help of current experimental data on three neutrino mixing angles. First of all, we assume $\delta_{p\gamma} = \delta_{pp} = 0$ and

[¶]Note that these results are obtained by using the old reactor antineutrino fluxes [16]. If the new reactor antineutrino fluxes [17] are used, the corresponding best-fit values and 1σ ranges of $\sin^2 \theta_{12}$ and $\sin^2 \theta_{13}$ will be shifted by about $+0.006$ and $+0.004$, respectively, but the result of $\sin^2 \theta_{23}$ is essentially unchanged [16].

use Eq. (7) to describe the relationship between R_0 and κ . Fig. 1 shows the allowed region of R_0 versus $0 \leq \kappa \leq 1$, where the 1σ ranges of θ_{12} , θ_{13} and θ_{23} together with $\delta \in [0, 2\pi)$ have been scanned. The central value of R_0 for a given value of κ is calculated by inputting the best-fit values of three neutrino mixing angles (i.e., $\sin^2 \theta_{12} = 0.306$, $\sin^2 \theta_{13} = 0.021$ and $\sin^2 \theta_{23} = 0.42$ [16]) and taking $\delta = 0$. Although the uncertainties associated with four neutrino mixing parameters remain rather large, we have the following quantitative observations: (1) the magnitude of R_0 is restricted to the range $0.18 \leq R_0 \leq 0.58$; (2) R_0 lies in the range $0.18 \leq R_0 \leq 0.31$ for the pure $p\gamma$ interaction (i.e., $\kappa = 1$); and (3) R_0 lies in the range $0.45 \leq R_0 \leq 0.58$ for the pure pp interaction (i.e., $\kappa = 0$). As the neutrino mixing parameters can be more and more precisely measured in the ongoing and future neutrino oscillation experiments, we expect that the GR will serve as a clear discriminator of UHE cosmic neutrinos originating from pp and $p\gamma$ collisions at an astrophysical source.

Now let us examine possible effects of $\delta_{p\gamma}$ and δ_{pp} on the relationship between R_0 and κ . For simplicity, we only take the best-fit values of three neutrino mixing angles and assume $\delta = 0$ in our numerical illustration. The change of R_0 with respect to three source parameters κ , $\delta_{p\gamma}$ and δ_{pp} is shown in Fig. 2, where $\delta_{p\gamma} \in [0, +0.2]$ and $\delta_{pp} \in [-0.2, +0.2]$ have been assumed. Note that $\delta_{p\gamma}$ is positive (or vanishing) by definition, while δ_{pp} can be either positive or negative (or vanishing), corresponding to an excess of the π^- or π^+ events (or $\Phi_{\pi^+}^{pp} = \Phi_{\pi^-}^{pp}$) in the pp interaction at an astrophysical source. As in Fig. 1, the central curve of R_0 varying with κ in Fig. 2 is obtained in the assumption of $\delta_{p\gamma} = \delta_{pp} = 0$. It is straightforward to see that $\delta_{p\gamma}$ and δ_{pp} can significantly affect R_0 for a given value of κ . For the pure $p\gamma$ interaction with $\kappa = 1$, a variation of $\delta_{p\gamma}$ from 0 to 0.2 results in a change of R_0 by more than 30% as compared with its original value. As indicated by Eq. (6), it is in principle possible to determine or constrain the free parameter $\delta_{p\gamma}$ (or δ_{pp}) for a given source with the pure $p\gamma$ (or pp) interaction by measuring R_0 at a neutrino telescope.

If the uncertainties from both the neutrino mixing parameters (θ_{12} , θ_{13} , θ_{23} and δ) and the source parameters ($\delta_{p\gamma}$ and δ_{pp}) are taken into account, it will be almost impossible to distinguish between $p\gamma$ and pp collisions even if $R_0 \sim 0.4$ is extracted from a neutrino telescope experiment. This observation implies that it *does* make sense for us to consider the nontrivial effects of $\delta_{p\gamma}$ and δ_{pp} . What we can do at present is to carefully study the yields of π^\pm fluxes in the realistic models of $p\gamma$ and pp collisions, so as to obtain some theoretical constraints on $\delta_{p\gamma}$ and δ_{pp} [20]. In addition, we must determine the neutrino mixing parameters as precisely as possible in all the terrestrial neutrino oscillation experiments.

3 Estimate of the Event Rate and Background

To further illustrate, let us estimate the event rate of the GR signal and the relevant background. We assume the total flux of UHE cosmic neutrinos and antineutrinos originating from an optically thin source to saturate the Waxman-Bahcall (WB) bound [21]

$$E_\nu^2 \Phi_{\nu+\bar{\nu}} = 2 \times 10^{-8} \epsilon_\pi \xi_z \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (10)$$

where ϵ_π stands for the ratio of the pion energy to the initial proton energy, and $\xi_z \approx 3$ for a source evolution $\propto (1+z)^3$ with z being the redshift. We have $\epsilon_\pi = \epsilon_\pi^{p\gamma} \approx 0.25$ for $p\gamma$ collisions or $\epsilon_\pi = \epsilon_\pi^{pp} \approx 0.6$ for pp collisions. Therefore, the WB bound actually depends on whether the pp or $p\gamma$ collision is assumed. Since there is on average one cosmic-ray neutron produced per proton collision, we may parametrize $\Phi_{\nu+\bar{\nu}}$ saturating the WB bound as

$$E_\nu^2 \Phi_{\nu+\bar{\nu}} = 6 \times 10^{-8} [(1 - \kappa') \epsilon_\pi^{pp} + \kappa' \epsilon_\pi^{p\gamma}] \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (11)$$

where κ' denotes the fraction of the $p\gamma$ collisions. In this parametrization $\kappa' = 1$ and $\kappa' = 0$ correspond to the pure $p\gamma$ and pure pp interactions, respectively. Note that we have defined κ in Eq. (1) as the fraction of the pion fluxes from the $p\gamma$ collisions. The relationship between κ and κ' can be easily established:

$$\kappa' = \frac{\kappa \epsilon_\pi^{pp}}{(1 - \kappa) \epsilon_\pi^{p\gamma} + \kappa \epsilon_\pi^{pp}}. \quad (12)$$

Given the total flux of neutrinos and antineutrinos in Eq. (11) and their flavor distribution at the source in Eq. (2), it is then possible to calculate the neutrino and antineutrino fluxes of different flavors at a neutrino telescope by taking account of the effect of flavor oscillations. We obtain

$$\begin{aligned} \Phi_{\nu_\alpha}^T &= \Phi_0 \frac{\epsilon_\pi^{pp} \epsilon_\pi^{p\gamma}}{(1 - \kappa) \epsilon_\pi^{p\gamma} + \kappa \epsilon_\pi^{pp}} \times \left\{ \frac{1}{3} \left[\frac{1}{2 + \delta_{pp}} + \frac{1 + \delta_{pp} - \delta_{p\gamma}}{(2 + \delta_{pp})(1 + \delta_{p\gamma})} \kappa \right] P_{e\alpha} + \frac{1}{3} P_{\mu\alpha} \right\}, \\ \Phi_{\bar{\nu}_\alpha}^T &= \Phi_0 \frac{\epsilon_\pi^{pp} \epsilon_\pi^{p\gamma}}{(1 - \kappa) \epsilon_\pi^{p\gamma} + \kappa \epsilon_\pi^{pp}} \times \left\{ \frac{1}{3} \left[\frac{1 + \delta_{pp}}{2 + \delta_{pp}} - \frac{1 + \delta_{pp} - \delta_{p\gamma}}{(2 + \delta_{pp})(1 + \delta_{p\gamma})} \kappa \right] P_{e\alpha} + \frac{1}{3} P_{\mu\alpha} \right\}, \end{aligned} \quad (13)$$

where Eq. (3) has been used and $\Phi_0 \equiv 6 \times 10^{-8} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} (1 \text{ GeV}/E_\nu)^2$ is defined. Note that the energy dependence of ν_α and $\bar{\nu}_\alpha$ fluxes in Eq. (13) has been suppressed.

Following Ref. [9], we estimate the event rate of the GR signal in the IceCube experiment:

$$dN_s/dt = 66.7\% \times N_{\text{eff}} \Delta\Omega \int dE_\nu \Phi_{\bar{\nu}_e}^T(E_\nu) \sigma_{\text{GR}}(E_\nu), \quad (14)$$

in which the coefficient 66.7% is the branching ratio of hadronic W^- decays, $N_{\text{eff}} \approx 6 \times 10^{38}$ denotes the number of target electrons for an effective volume $V_{\text{eff}} \sim 2 \text{ km}^3$ of the IceCube detector, $\Delta\Omega \approx 2\pi$ is the solid angle aperture, and $\sigma_{\text{GR}}(E_\nu) = \pi g^2 M_W^2 \delta(2m_e E_\nu - M_W^2)/(4m_e E_\nu)$ is the cross section of the GR scattering. The typical GR signal is the shower events induced by the hadronic decays of W^- in the resonant energy region, while the main background comes from the non-resonant inelastic scattering of ν_e and $\bar{\nu}_e$ with nucleons in the detector. As for the background events, the effective number of target nucleons is approximately twice the number of electrons (i.e., $N'_{\text{eff}} \approx 1.2 \times 10^{39}$) and the solid angle aperture is $\Delta\Omega' \approx 4\pi$. The cross sections of charged-current $\nu_e N$ and $\bar{\nu}_e N$ interactions are well represented by the power-law forms [8]:

$$\begin{aligned} \sigma_{\text{CC}}^{\nu N}(E_\nu) &= 2.69 \times 10^{-36} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}} \right)^{0.402}, \\ \sigma_{\text{CC}}^{\bar{\nu} N}(E_\nu) &= 2.53 \times 10^{-36} \text{ cm}^2 \left(\frac{E_\nu}{1 \text{ GeV}} \right)^{0.404}. \end{aligned} \quad (15)$$

Integrating over the resonant acceptance energy bin ($10^{6.7} \dots 10^{6.9}$) GeV for the IceCube telescope, we can obtain the event rate for the background

$$dN_b/dt = N'_{\text{eff}} \Delta\Omega' \int_{10^{6.7} \text{ GeV}}^{10^{6.9} \text{ GeV}} dE_\nu \left[\Phi_{\nu_e}^T(E_\nu) \sigma_{CC}^{\nu N}(E_\nu) + \Phi_{\bar{\nu}_e}^T(E_\nu) \sigma_{CC}^{\bar{\nu} N}(E_\nu) \right]. \quad (16)$$

As usual, the signal-to-background ratio can be defined as $R_{s/b} \equiv (dN_s/dt)/(dN_b/dt)$, which measures the significance of the signal events.

We perform a numerical calculation of the event rate of the GR signal dN_s/dt and the signal-to-background ratio $R_{s/b}$, and examine their dependence on the source parameters $(\kappa, \delta_{p\gamma}, \delta_{pp})$ and the neutrino mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta)$. Fig. 3 shows the expected event rate dN_s/dt versus $0 \leq \kappa \leq 1$, where $\delta_{p\gamma} = \delta_{pp} = 0$ is assumed and the 1σ ranges of θ_{12} , θ_{13} and θ_{23} together with $\delta \in [0, 2\pi)$ have been scanned. The corresponding signal-to-background ratio in this case is shown in Fig. 4. For the pure pp interaction (i.e., $\kappa = 0$), we obtain $dN_s/dt \approx 3.5$ per year and $R_{s/b} \approx 5$, indicating a great discovery potential of the IceCube telescope after several years of data accumulation [9]. For the pure $p\gamma$ interaction (i.e., $\kappa = 1$), however, the event rate is quite low: $dN_s/dt \approx 0.8$ per year. Hence it is quite challenging for the IceCube detector to discover UHE cosmic neutrinos originating from an optically thin source with the pure $p\gamma$ collisions. This observation justifies the importance of the GR channel in distinguishing between pp and $p\gamma$ interactions. On the other hand, the dependence of dN_s/dt and $R_{s/b}$ on the source parameters $(\kappa, \delta_{p\gamma}, \delta_{pp})$ are illustrated in Fig. 5 and Fig. 6, where the best-fit values of three neutrino mixing angles (i.e., $\sin^2 \theta_{12} = 0.306$, $\sin^2 \theta_{13} = 0.021$ and $\sin^2 \theta_{23} = 0.42$ [16]) together with $\delta = 0$ have been input. It is straightforward to see the degeneracy between the uncertainty induced by those neutrino mixing parameters and that by the source parameters $(\delta_{p\gamma}, \delta_{pp})$. So a full determination of the latter requires more precise values of neutrino oscillation parameters and a neutrino telescope whose scale should be much larger than the IceCube detector.

4 Summary

We have re-examined the possibility of using the GR channel $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$ to discriminate between the UHE cosmic neutrinos originating from $p\gamma$ and pp collisions in an optically thin source of cosmic rays. After proposing a general parametrization of the initial neutrino flavor distribution by taking account of non-zero $\delta_{p\gamma}$ and δ_{pp} at the source, we have established an analytical relationship between the typical source parameter κ and the working observable of the GR R_0 at a neutrino telescope. We have also illustrated the numerical dependence of R_0 on κ with the help of the latest experimental data on three neutrino mixing angles. We find that a measurement of R_0 is in principle possible to identify the pure $p\gamma$ interaction ($\kappa = 1$), the pure pp interaction ($\kappa = 0$) or a mixture of both of them ($0 < \kappa < 1$) at a given source of UHE cosmic neutrinos. In addition, the event rate of the GR signal against the relevant background is estimated by assuming the total flux of UHE cosmic neutrinos and antineutrinos originating from an optically thin source to saturate the WB bound.

A measurement of the GR and a determination of the flavor distribution of UHE cosmic neutrinos at an astrophysical source are certainly big challenges to the IceCube detector and other possible neutrino telescopes. Anyway, our present understanding of the production mechanism of UHE cosmic neutrinos depends on a number of hypotheses and thus needs more and more observational supports. We therefore expect that neutrino telescopes can help us in this connection in the long run.

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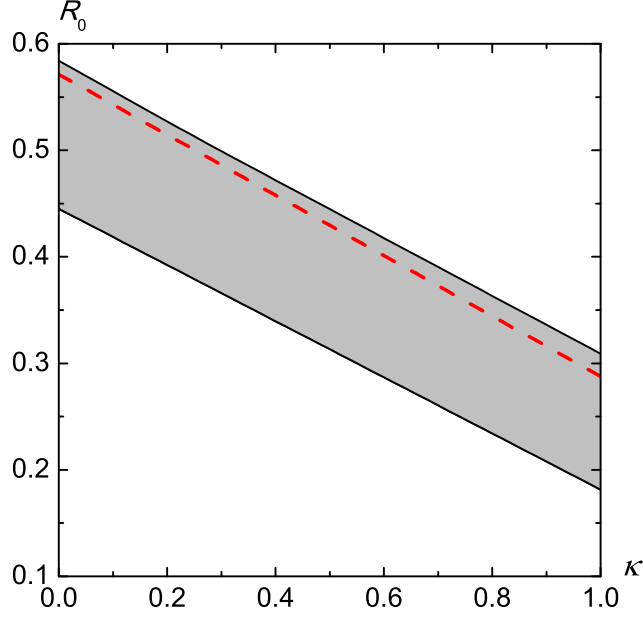


Figure 1: The dependence of the working observable R_0 on the source parameter κ in the assumption of $\delta_{p\gamma} = \delta_{pp} = 0$. The dashed curve corresponds to the best-fit values of θ_{12} , θ_{13} and θ_{23} together with $\delta = 0$, and the uncertainties come from the 1σ error bars of three neutrino mixing angles and an arbitrary change of $\delta \in [0, 2\pi)$.

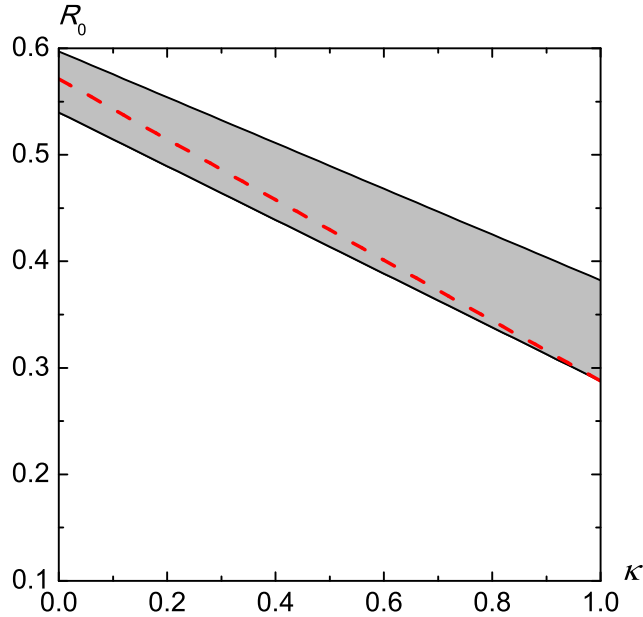


Figure 2: The dependence of the working observable R_0 on the source parameter κ , where the best-fit values of θ_{12} , θ_{13} and θ_{23} together with $\delta = 0$ have been taken. The dashed curve corresponds to $\delta_{p\gamma} = \delta_{pp} = 0$, and the uncertainties come from the variations of $\delta_{p\gamma}$ and δ_{pp} in the ranges $\delta_{p\gamma} \in [0, +0.2]$ and $\delta_{pp} \in [-0.2, +0.2]$.

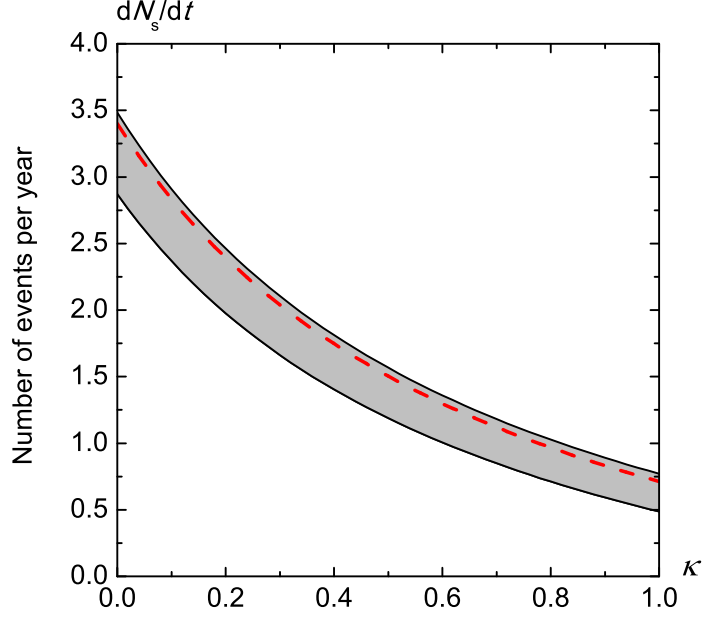


Figure 3: The dependence of the event rate of the GR signal dN_s/dt on the source parameter κ in the assumption of $\delta_{p\gamma} = \delta_{pp} = 0$. The dashed curve corresponds to the best-fit values of θ_{12} , θ_{13} and θ_{23} together with $\delta = 0$, and the uncertainties come from the 1σ error bars of three neutrino mixing angles and an arbitrary change of $\delta \in [0, 2\pi)$.

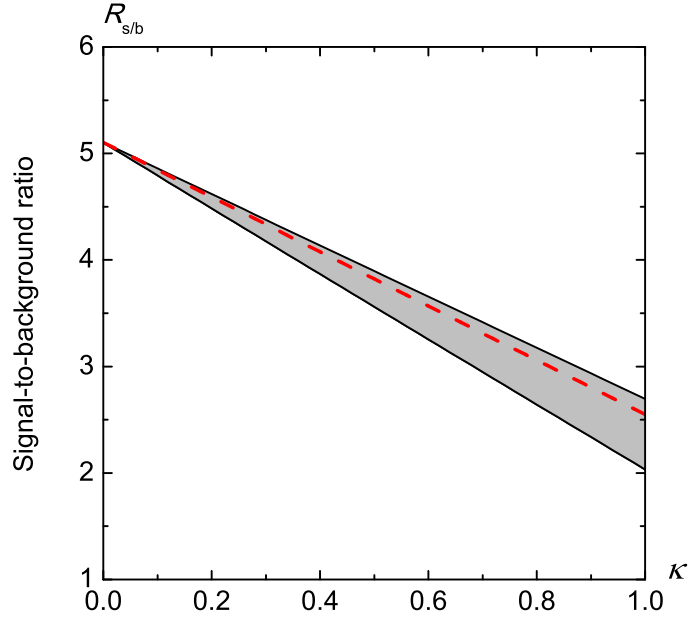


Figure 4: The dependence of the signal-to-background ratio $R_{s/b}$ on the source parameter κ in the assumption of $\delta_{p\gamma} = \delta_{pp} = 0$. The dashed curve corresponds to the best-fit values of θ_{12} , θ_{13} and θ_{23} together with $\delta = 0$, and the uncertainties come from the 1σ error bars of three neutrino mixing angles and an arbitrary change of $\delta \in [0, 2\pi)$.

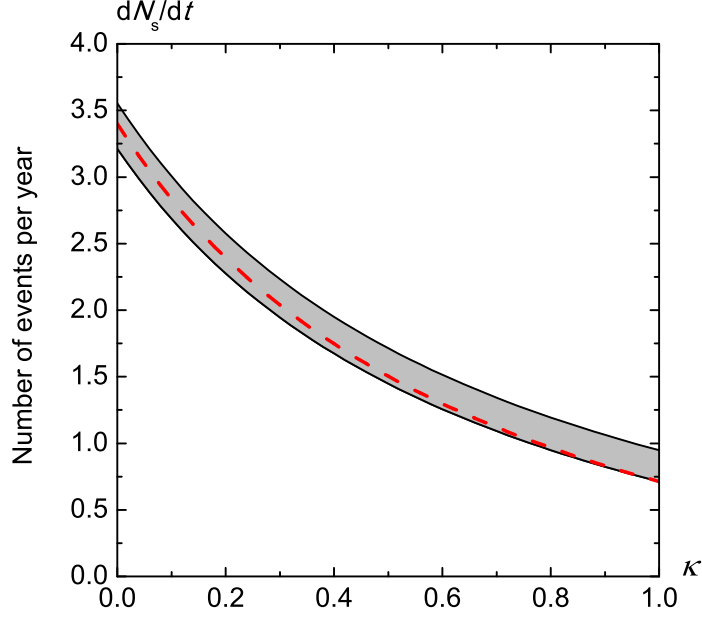


Figure 5: The dependence of the event rate of the GR signal dN_s/dt on the source parameter κ , where the best-fit values of θ_{12} , θ_{13} and θ_{23} together with $\delta = 0$ have been taken. The dashed curve corresponds to $\delta_{p\gamma} = \delta_{pp} = 0$, and the uncertainties come from the variations of $\delta_{p\gamma}$ and δ_{pp} in the ranges $\delta_{p\gamma} \in [0, +0.2]$ and $\delta_{pp} \in [-0.2, +0.2]$.

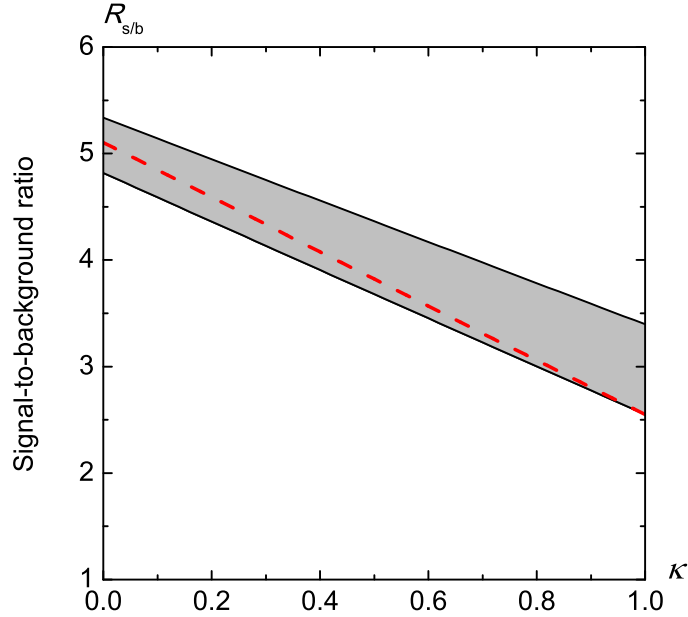


Figure 6: The dependence of the signal-to-background ratio $R_{s/b}$ on the source parameter κ , where the best-fit values of θ_{12} , θ_{13} and θ_{23} together with $\delta = 0$ have been taken. The dashed curve corresponds to $\delta_{p\gamma} = \delta_{pp} = 0$, and the uncertainties come from the variations of $\delta_{p\gamma}$ and δ_{pp} in the ranges $\delta_{p\gamma} \in [0, +0.2]$ and $\delta_{pp} \in [-0.2, +0.2]$.